Meteorite Spectroscopy and Characterization of Asteroid Surface Materials

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The purpose of this research effort is to improve our understanding of the origin, evolution, and inter-relationships of the asteroids; of their relationships to the meteorites; and of the conditions and processes in the early inner solar system. The surface mineral assemblage and the surface heterogeneity of selected minor planets is determined from analysis of telescopic spectra to provide the data base to accomplish these goals.

The asteroids represent the sole surviving, *in situ* remnants of the population of planetesimals which accreted to form the Earth and other terrestrial planets. The meteorites are samples of some of these asteroidal bodies, but the specific source bodies of the individual meteorites or meteorite groups have not been established. Thus the detailed meteoritic evidence cannot be directly placed into a spatial context in the early solar system. The meteorites provide a good "clock" for events and conditions in the late nebular and early accretionary period of solar system history, but they provide a poor "map".

The analysis of asteroidal visible and near-infrared (VNIR) reflectance spectra compliments meteorite studies as a means of probing the late nebular through early post-accretionary period of solar system history. Although surface material characterizations from VNIR reflectance spectrophotometry cannot achieve the detail or the level of sophistication attainable in the laboratory analysis of meteoritic specimens, such remote sensing studies do provide valuable and unique information on material whose *location* in the early solar system can be established with some certainty. Asteroid spectral studies also provide insight into the incompleteness in the meteorite sample and into the types of additional assemblages which are present on asteroids.

The particular type of material present on a specific asteroid provides direct insight into the nebular or post-accretionary processes in the early solar system at that particular semi-major axis. As the number of characterized asteroids increases, so does the completeness of this "map" of early processes and conditions. The combination of temporal constraints from meteoritic studies and spatial constraints from asteroid spectral characterizations provides the most powerful available means of investigating the formation epoch.

This research program involves five complimentary efforts, including:

1) the development of *quantitative* interpretive calibrations and procedures for the analysis of VNIR spectral data from laboratory spectral studies of the meteoritic and meteorite-like assemblages which are appropriate analogues to asteroidal materials [e.g. Gaffey, 1986a; Cloutis *et al.*, 1986],

2) the reduction and calibration of high precision VNIR telescopic data of asteroids selected as particularly relevant to major issues in asteroid or meteorite science,

3) the analysis of that asteroid VNIR spectral data using the most sophisticated available interpretive calibrations and methodologies to derive quantitative or semi-quantitative determinations of surface mineralogy, phase abundance, and the mineralogic nature and lateral extent of large scale lithologic units on the surface [e.g. Gaffey, 1983, 1984],

4) the utilization of these surface material characterizations to constrain the evolution of individual asteroids, such as the presence and intensity of any post-accretionary thermal events, the degree of metamorphism or magmatic differentiation, and the nature and extent of

the subsequent collisional processes [e.g. Gaffey, 1984], and
5) the synthesis of this information on individual asteroids into models of the inter-relationships between the various asteroid groups, the post-accretionary collisional and thermal history of regions and populations in the asteroid belt, and the implications for the accretion and early evolution of the terrestrial planets [e.g. Gaffey, 1986b].

This multidiscipline approach, combining in a single program all the major aspects of the work, has proven particularly efficient. It allows each aspect to be better focused on the central issues. For example, calibration work can be better directed toward satisfying the most pressing needs in the interpretive area; the observations can be specific to the questions being addressed rather than simply part an uncoordinated general survey; and the analysis can effectively communicate its most urgent needs for specific calibrations or for observations of a particular type.

However, in any asteroidal research beyond the most general type of survey observations (i.e. in the first pass, one observes whatever happens to be available), the quality of the scientific contribution which is produced depends significantly on the appropriateness and sophistication of the formulation of the original question. A major focus of this research program is the issue of asteroidal thermal and collisional evolution.

The relative proportion of S-type asteroids decreases rapidly with increasing semi-major axis across the asteroid belt. This has been interpreted to indicate that either: a) the belt represents a transition region between the zones of formation of ordinary chondrite-type and the carbonaceous chondrite-type assemblages by nebular processes, or b) the inner portion of the belt has undergone a strong post-accretionary heating event which altered the original material in that region.

In the first alternative, the general population pattern in the belt is the fossil signature of the radial compositional variation of the accreting solar nebula. In principle, once that pattern is understood, the temperature and pressure of the nebula could be strongly constrained at that particular distance from the proto-sun. In the second case, the radial variation in the asteroid population is the signature of a radially dependent heating event in the early post-accretionary period which was superimposed upon the previous nebular material. It is plausible or probable that such a heating event would have also affected the planetesimals in the zones of the terrestrial planets. In that case, the early thermal structure and processes (core formation, atmospheric outgassing rates, etc.) of the terrestrial planets, which accreted from such a population of planetesimals, would be a strong function of the thermal state these planetesimals. An Earth accreted from warm, magmatically differentiated planetesimals would have a profoundly different early history than one accreted from cold, undifferentiated planetesimals, even though both would have chondritic bulk compositions.

To date, essentially all available spectral evidence has strongly indicated that the large S-type asteroids are predominantly thermally evolved, magmatically differentiated bodies [see, Gaffey, 1984; Gaffey, 1986a,b). It is also now evident that the variation in UBV colors of the S-type asteroids with semi-major axis (Dermott et al., 1985) is a manifestation of a systematic mineralogic variation within the S-type population, these objects becoming more metal- and pyroxene-rich and more olivine-poor with increasing orbital distance (Gaffey, 1986b). This pattern is the reverse of that expected from an undifferentiated, chondritic planetesimal population. The relationships indicate that indeed the S-type are primarily thermally-evolved bodies, and that the innermost S-type objects underwent the most intense heating and differentiation while the outer S-types underwent substantial reduction of oxidized iron with either

strong metamorphism or partial melting. Work is underway using 52-color survey spectra (Bell et al., 1985) to refine this picture.

Analysis of rotationally resolved reflectance spectra has been used to derive a litholoic unit map for 4 Vesta (Gaffey, 1983; and in preparation), to investigate asteroid surface heterogeneity (Gaffey, et al., 1982), and to test the chondritic affinities of 8 Flora (Gaffey, 1984).

Present work is concentrated on 15 Eunomia, the largest S-type asteroid. Observations in December, 1981 produced 101 24-filter spectra (0.35-1.00um) and 66 120-channel VNIR CVF spectra (0.65-2.55um). These exhibit rotational variations which are being analyzed to determine the nature of the hemispheric mineralogic variations which produce the variations.

In addition, the flux variations in each filter or channel provides a lightcurve for Eunomia at that bandpass. In a cooperative program with S.J. Ostro (JPL), these monochromatic lightcurves are being inverted by his technique (Ostro and Connelly, 1984) to derive an equivalent equatorial profile of the body. Since the physical shape of the body is invariant, differences between the profiles at different wavelengths must arise from surface reflectance variations. Combined with the subhemispheric mineralogic variations determined from the analysis of the spectra at different rotational aspects, the variations of the complex profile within and outside mineralogically diagnostic spectral intervals will permit determination of lithlogic boundaries and, if Eunomia is an intact core fragment, constrain the litho-stratigraphic structure within the parent planetesimal. This should significantly increase our understanding of the nature of the magmatic differentiation processes in asteroid sized bodies.

References

Bell, J.F, B.R. Hawke, P.D. Owensby, and M.J. Gaffey (1985) The 52-color asteroid survey: Results and interpretation. Bull. A.A.S. 17, 729.

Cloutis, E.A., M.J. Gaffey, T.L. Jackowski, K.L. Reed (1986) Calibrations of phase abundance, composition, and particle size distribution for olivine-orthopyroxene mixtures from reflectance spectra. J. Geophys. Res. 91, 11,641-11,653.

Dermott, S.F., J. Gradie, and C.D. Murray (1985) Variation of the UBV colors of S-class asteroids with semimajor axis and diameter. Icarus 62, 289-297.

Gaffey, M.J. (1983) The asteroid (4) Vesta: Rotational spectral variations, surface material heterogeneity, and implications for the origin of the basaltic achondrites. Lunar Planet. Sci. XVI, 231-232.

Gaffey, M.J. (1984) Rotational spectral variations of Asteroid (8) Flora: Implications for the nature of the S-type asteroids and for the parent bodies of the ordinary chondrites. Icarus 60 83-114.

Gaffey, M.J. (1986a) The spectral and physical properties of metal in meteorite assemblages: Implications for asteroid surface materials. Icarus 66, 468-486.

Gaffey, M.J. (1986b) Evolution of the inner asteroid belt: Paradigms and paradoxes from spectral studies. Meteoritics 21.

Gaffey, M.J., T. King, B.R. Hawke, and M.J. Cintala (1982) Spectral variations on asteroidal surfaces: Implications for composition and surface processes. in Workshop on Lunar Breccias and Soils and Their Meteoritic Analogs (G.J. Taylor and L.L. Wilkening, Eds.), LPI TR 82-02, Lunar and Planetary Institute, Houston, pp. 40-43.

Ostro, S.J. and R. Connelly (1984) Complex profiles from asteroid lightcurves. Icarus 57, 443-463.